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FINAL REPORT

to the

Office of Naval Research

Contract N6onr-266, Task Order VIII

NR 081-002

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August 31, 1954

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Final Report
on Contract N6onr-266, Task Order VIII,
NR 081-002
between the Office of Naval Research
and The University of Texas

Contract N6onr-266 was effective for the period March 1, 1948, to August 31, 1954. The study of the physical properties of rocks and minerals under high pressure and temperature was the fundamental objective of work under this contract. Attention was actually centered chiefly on elastic properties and wave velocities. Apparatus developed and constructed permitted measurements up to 10,000 bars hydrostatic pressure and 300°C. Equipment recently completed should permit extending the temperature range to some 600°C. During the term of the contract, twelve students were employed as research assistants. Nine Master of Science and three Doctor of Philosophy degrees were granted for research completed.

Ten technical reports describing various phases of the work were submitted and nine of these were published in scientific journals.

A detailed review of the work can best be given by reproducing the abstracts of the technical reports.

REPORT NUMBER 1 — January 1949

Pulses are generated at one end of a cylindrical rod by a quartz crystal. A second crystal at the opposite end is used as a detector. The transmission time is studied as a function of rod length, diameter, and material. In general, a single input pulse gives rise to several pulses at the detector. For the dimensions and rise times used, all of the arrivals are explicable in terms of transmission with either the dilatational or rotational velocity of the material or a combination of both. The rotational and dilatational velocities can be computed from these data, and hence the elastic constants of the material.

REPORT NUMBER 2 September 1949

The variations in velocity of dilatational waves in the pressure range 0 - 15,000 p.s.i. and temperature range 30°C to 90°C have been measured for samples of polystyrene, lucite, and polyethylene. The velocity of rotational waves was also measured for polystyrene and lucite. In polyethylene no trace of a rotational wave could be identified. The elastic moduli and Poisson's ratio are computed over the experimental range.

REPORT NUMBER 3 December 1949

Using pulse methods recently developed, the dilatational and rotational velocities of several igneous rocks have been measured in the pressure range 0 - 15,000 p.s.i. and temperature range 30°C to 150°C. From these values the elastic moduli are computed. Important members of the acidic intermediate, and basic families were selected for investigation. The effect of admitting or excluding the pressure fluid from the rock was investigated. Some results on the effect of grain size were obtained.

REPORT NUMBER 4 May 1950

From a study of the transmission of dilatational pulses through rods it has been found possible to calculate not only the dilatational velocity but also the rotational velocity. From these velocities the elastic moduli of isotropic materials can be computed. The results are insensitive to boundary conditions and hence the method can be used when the material is surrounded by oil in a pressure chamber.

The velocities in sedimentary rocks have been measured in the ranges 0 - 1100 kg/cm^2 and 25 - 175°C. In addition, one limestone and one dolomite have been measured up to 2000 kg/cm^2. The dilatational and rotational velocities and the elastic moduli as a function of pressure and temperature are presented for selected samples. A comparison of our results with those obtained by other methods is given. Although our measurements are based on pulses which have an equivalent frequency of 2.0 - 6.0 megacycles, there is no apparent discrepancy with low frequency

and static measurements. This would indicate that at least for the rocks for which a comparison can be made, dispersion is not important. The elastic moduli are computed as functions of depth with an assumed gradient of 9.5°C per 1000 feet. Values of Poisson's ratio are constant, or increase slightly over the experimental range.

REPORT NUMBER 5 September 1950

The transmission of elastic pulses through solid rods has been investigated. A single input pulse gives rise to a series of pulses from which it has been found possible to compute both the dilatational and rotational velocities in the material. From these velocities the elastic moduli of isotropic materials may be computed. The mode of transformation of the input pulse has been studied and provides a thorough check of the computational procedure. Two materials, pyrex glass and brass have been studied. The moduli have been measured as functions of pressure and temperature up to 50,000 p.s.i. and 200°C.

REPORT NUMBER 6 April 1951

The variation in dilatational and rotational velocities in rock samples with pressure and temperature has been studied. The measurements were taken at pressures from 1 bar (atmospheric) to 5,000 bars, and temperatures of 25°C to 200°C for all samples and up to 300°C for two samples. We can thus reach a pressure equivalent to some 18 km or 60,000 feet of burial but our highest available temperature probably at most corresponds to no more than 8-9 km.

The measured rotational velocities check very well with independent measurements. Laboratory measurements of the dilatational velocity are not available for comparison. From the measured dilatational and rotational velocities, the elastic moduli and Poisson's ratio may be computed. Values of Poisson's ratio are tabulated for all samples. In general, highly quartzitic rocks have low values 0.13 - 0.20 whereas the majority of rocks have values in the range 0.26 - 0.33.

The effect of interstitial water has been investigated in one sandstone and one limestone. The sandstone shows an increase in velocity at low pressure and a decrease at high pressure whereas the limestone shows the opposite effect.

REPORT NUMBER 7 June 1951

The propagation of an elastic pulse through the simple geometric forms, rods and plates, is investigated from a theoretical point of view with the aid of the small-motion dynamic elastic equations of an isotropic, homogeneous, dissipationless solid.

The investigation is restricted to disturbances which are initially plane-wave pulses of dilatation, and formal solutions are developed by Fourier transform methods (symmetric and one sided). The resulting formal solutions are developed into infinite series, the terms of which represent the total contribution of wave-groups which can be associated with the paths of minimum transit time predicted by the methods of geometrical optics.

These paths, and the associated wave-groups, are found to be characterized by two integers n_1 and n_2 which represent the number of times the thickness of the plate (or diameter of the rod) has been traversed as a dilatational wave and as a rotational wave respectively. The variety in these paths is found to result from conversions of dilatational wave energy to rotational wave energy at the free surfaces. When the Poisson ratio, σ, is zero, this conversion effect does not exist for the disturbances considered, and all of the energy is carried by the direct dilatational wave ($n_1 = n_2 = 0$).

The terms of these series are simplified by contour deformation methods and are found to represent transients with the minimum transit times predicted by the methods of geometrical optics. In the case of the plate, the simplification enables one to carry out finite numerical integrations in obtaining quantitative data on the pulse shape and amplitude of the disturbances associated with any specific values of n_1 and n_2.

Various interference effects are found between these wave-groups as $t \rightarrow \infty$ and/or the distance of transmission $\rightarrow \infty$. It is shown that these wave-groups interfere in such a way that the total disturbance becomes asymptotically a plane-wave travelling with the velocity predicted in the classical theories of thin plates and rods.

A comparison is made of these theoretical considerations and the experiments reported by Hughes, Pondrom and Mims[1], and their failure to identify any wave-groups other than those corresponding to the direct dilatational and critical angle paths (all of which have $n_1 = 0$) is explained.

[1]D. S. Hughes, W. L. Pondrom, and R. L. Mims, Phys. Rev. 75, 1552-1556 (1949)

REPORT NUMBER 8 — December 1952

The velocity of dilatational waves in four sandstones has been measured as a function of pressure in the range 50 to 1000 bars at room temperature and at 100°C. At least two cores from each sample were run, one dry and one saturated with water. In addition two cores from one sample were run at several partial saturations. The porosities of the samples varied from about 8 to 20 percent. The effect of water content is dependent on pressure. At low pressures (50 bars) the velocity rises sharply at small saturations (0 - 10 percent), remains constant with saturation 10 to 90 percent and then decreases as the saturation approaches 100 percent. At 50 bars the velocity at 100 percent saturation is generally higher than that at 00 percent saturation. Even for the one exception an extrapolation would indicate this to be true at atmospheric pressure. As the pressure is increased the rise at low saturations decreases; at 500 bars it disappears. The velocity is almost constant with saturation until about 90 percent saturation is reached. It then decreases rapidly as 100 percent saturation is approached.

A qualitative explanation of these results is given.

REPORT NUMBER 9 December 1952

The changes in pore volume of jacketed dry sandstone samples have been measured under hydrostatic pressures over the range 50 to 1,000 bars (14,504 p.s.i.). The percent change in pore volume at each pressure and the pressure coefficient of change of pore volume have been computed. All measurements were made at room temperature.

The total change in pore volume when the hydrostatic pressure was increased from 50 to 1,000 bars was found to be about 7.5 percent of the pore volume for a sample of Steven sandstone (porosity 18.5 percent) and approximately 3.0 percent of the pore volume for a sample of Berea sandstone (porosity 10.4 percent).

The coefficient of change of pore volume with pressure is found to decrease rather rapidly with increasing pressure up to around 500 bars. Thus pressure changes applied to rock become much more important when the original geostatic load on the rock is small.

REPORT NUMBER 10 June 1953

Expressions for the velocities of elastic waves in stressed solids are derived using Murnaghan's theory of finite deformations and third-order terms in the energy. For isotropic materials, in addition to the Lamé constants λ and μ, three additional constants, ℓ, m, and n, are required to describe the material.

By measuring the transmission time of elastic pulses through the material, the velocities of longitudinal and shear waves are determined as a function of applied stress. By subjecting the material to hydrostatic pressure as well as simple compression, it is found that seven functions of the three constants ℓ, m, and n can be measured and thus numerical values calculated. Results are given for polystyrene, iron, and Pyrex glass.

August 31, 1954
DSH:lw

I have greatly enjoyed working with the Office of Naval Research on this project and should like to express my sincerest gratitude for their very generous support.

D. S. Hughes
Director
Contract N6onr-266
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